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14. ABSTRACT
Normal incident acoustic techniques were used to determine values of sediment properties (acoustic impedance, sound speed, bulk density, porosity, shear strength, water content and mean grain size) and map those (acoustic impedance and grain size) in the northeastern Gulf of Mexico. The acoustic data were acquired using a 11 kHz normal incident echo sounder over approximately 2000 km of track line. A calibration factor for echo strength was determined by the comparison of acoustic data to measured impedance from five core samples (ground truth data). This echo strength calibration was used for the entire data set. Values of sediment properties were calculated from sediment impedance using the regressions compiled from the historical core database. Comparison of ground truth and echo strength to data from 20 additional core locations shows close agreement. Discrepancies are probably due to navigation errors or weak returns in deeper water. In addition, sediment disturbance and frequency dispersion can be considered. Using acoustic derived sediment properties, four sediment provinces of the study area are defined as the following types: sandy/silty clay (impedance, 1.6-2.0 10" kg/m2 s), sand-silt-clay and/or clayey sand (impedance, 2.01-2.40 IO6 kg/nrs), silt or fine sand (impedance, 2.41-2.90 106 kg/m2 s), medium/coarse sand (impedance, 2.91-4.0 106 kg/m2 s). The areal distributions of the four types coincide with the previous reports based on sediment sampling. Therefore, the acoustic technique can effectively be used to define and classify sediments and map sediment provinces.

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Sediment types determination using acoustic techniques in the Northeastern Gulf of Mexico

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ABSTRACT: Normal incident acoustic techniques were used to determine values of sediment properties (acoustic impedance, sound speed, bulk density, porosity, shear strength, water content, and mean grain size) and map those (acoustic impedance and grain size) in the northeastern Gulf of Mexico. The acoustic data were acquired using a 11 kHz normal incident echo sounder over approximately 2000 km of track line. A calibration factor for echo strength was determined by the comparison of acoustic data to measured impedance from five core samples (ground truth data). This echo strength calibration was used for the entire data set. Values of sediment properties were calculated from sediment impedance using the regressions compiled from the historical core database. Comparison of ground truth and echo strength to data from 20 additional core locations shows close agreement. Discrepancies are probably due to navigation errors or weak returns in deeper water. In addition, sediment disturbance and frequency dispersion can be considered. Using acoustic derived sediment properties, four sediment provinces of the study area are defined as the following types: sandy/silty clay (impedance, 1.6–2.0 10^6 kg/m^2 s), sand-silt-clay and/or clayey sand (impedance, 2.01–2.40 10^6 kg/m^2 s), silt or fine sand (impedance, 2.41–2.90 10^6 kg/m^2 s), medium/coarse sand (impedance, 2.91–4.0 10^6 kg/m^2 s). The areal distributions of the four types coincide with the previous reports based on sediment sampling. Therefore, the acoustic technique can effectively be used to define and classify sediments and map sediment provinces.

Keywords: sediment types, acoustic seafloor sediment classification, Gulf of Mexico

1. INTRODUCTION

Acoustic seafloor sediment classification system that can remotely estimate sediment type and geotechnical properties has been widely used in various fields of in marine geology, civil engineering, fisheries, and military science (Lambert, 1988; Lambert and Fiedler, 1991; Lambert et al., 1993, 2002; Walter et al., 1997, 1998, 2002; Richardson et al., 2002). Conventionally, seafloor sediment properties have been determined from core and grab sediments. This process is slow, labor intensive, expensive, and does not provide either real time or *in situ* data collection. Also the data represent only the properties of the sediments at a specific and limited location and do not provide quantification of the highly variable nature of shallow water sediments. On the other hand, acoustic seafloor sediment classification system has been able to accurately predict, in near real-time, acoustic properties (sound speed, acoustic impedance, and attenuation), sediment type (grain size), and a number of selected geotechnical properties (bulk density, porosity, and shear strength) of the upper several meters of the seafloor while in an underway survey (Lambert, 1988; Lambert and Fiedler, 1991; Lambert et al., 1993, 2002).

Sediment type in this study was determined from re-processing of acoustic data acquired by Acoustic Sediment Classifier System (ASCS) of Naval Research Laboratory (NRL). For re-processing of the data, Submarine Sediment Classifier (SSC) newly developed by NRL was used. The ASCS system has been successfully used to characterize sediment properties at Chesapeake Bay of Maryland, near the Dry Tortugas of Florida, and along the California Continental Shelf near the Eel River (Walter et al., 1997, 1998, 2002; Richardson et al., 2002). But the determination of sediment type using SSC is not known yet.

The objectives of this paper are to define sediment type (especially grain size), in the northeastern Gulf of Mexico, and to compare values of sediment properties measured in the laboratory from sediments collected with corers or grabs.

2. PHYSICAL SETTING

The northeastern Gulf of Mexico including the study area (Fig. 1) is micro-tidal with an average tidal range of 0.4 to 0.5 m. Tidal currents on the shelf are generally less than 15 cm/s (Schroeder et al., 1994; Clarke, 1994), whereas wind driven alongshore surface currents can be as high as 40–50 cm/s with strongest currents in the winter and early spring associated with the passage of cold fronts (Schroeder et al.,

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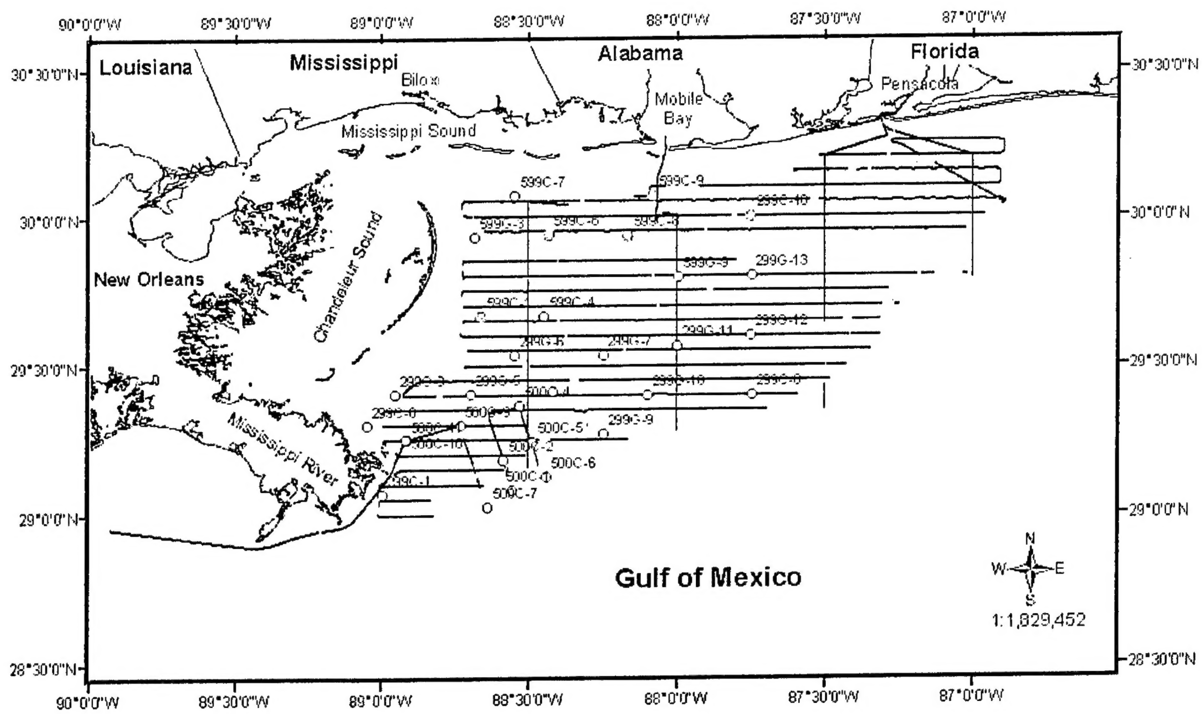

Fig. 1. Locations of core and grab and track lines. Five solid circles are core locations selected for determination of calibration factor of echo strength. Abbreviation C and G at station indicate core and grab locations, respectively.

1987). Tropical storms (Hurricanes) can generate strong currents up to 160 cm/s and rework sediments to water depths of 100 m (Moeller et al., 1993; Murray, 1970).

The Mississippi River, the largest sediment source in the Gulf of Mexico, is located in the southwestern part of the study area. This river system has been significantly influenced depositional patterns in the northern Gulf of Mexico (Coleman, 1988). According to Coleman (1988), the river currently discharges an average of 15,360 m^3/s of fresh water into the Gulf of Mexico, with maximum and minimum discharges of 57,900 and 2,830 m^3/s, respectively. Annual sediment discharge is estimated at about 6.21×10^{11} kg with 75% transported as bedload and 25% as suspended load (Fisk and McFarlan, 1954).

The northeastern shelf (shallower than 100 m in water depth) of the Gulf of Mexico has been strongly influenced by fluctuations of sea level during the Quaternary (Frazier, 1974; Beard et al., 1982). The water depth abruptly deepens southeastward from 150 to over 500 m. The shelf area is largely covered with relict sand (late Pleistocene and early Holocene age) and/or modern sandy and muddy deposits mainly originating from the Mississippi River (Mazzullo and Bates, 1985; Kindinger, 1989).

3. METHODS

3.1. Ground Truth Data

The core and grab samples (23 core and 8 grab sediment samples, Fig. 1) acquired during Northern Gulf Littoral Initiative (NGLI) project (Sawyer et al., 2001) are used both for calibration and as ground truth (impedance, sound speed, porosity, density, and mean grain size) for acoustic predictions. Non-destructive measurements to determine the physical properties of the core samples were only made on whole-round core sections utilizing Geotek Multi-Sensor Core Logger (MSCL; Schultheiss and McPhail, 1989). Core Logger data were acquired at constant intervals of 1 cm and periods of 2 seconds, from the top to bottom depth of each section of core after the sediment cores were equilibrated to ambient laboratory room temperature (approximately 23°C). The Core Logger uses a pair of 500 kHz piezo-electric ceramic transducer to measure p-wave velocity and wet bulk density is measured by gamma-ray attenuation, using a 137-Cs gamma source and scintillation counter. Derivative acoustic impedance and fractional porosity are additionally calculated for each sample interval. Fractional porosity values are reported relative to an average grain density value of 2.65 g/cm^3, and a pore water density of 1.026 g/cm^3. P-wave velocity values are reported at a standard laboratory temperature of 23°C and 35‰ salinity. Grab samples were only used for grain size analysis.

Surficial samples (~0–50 cm below the seafloor) were analyzed from core (10 cm intervals) and grab (0–10 cm) samples for grain size statistics The depth was determined based on a pulse length of 0.54 m based on a center frequency of 11 kHz and four wavelengths in the duration of the pulse (Walter, 1998) and sediment type. Classical siev-

ing techniques were utilized for the sand sized sediments (Folk, 1974), and the fine particles (silt and clay) were measured using pipette analysis and a Micromeritics Model 5000 Sedigraph (Briggs, 1994).

3.2. Acoustic Data from ASCS

The acoustic data for sediment classification was acquired using a 11 kHz normal incident echo sounder for approximately 2000 km of track line in the northeastern Gulf of Mexico during May 2000. Acoustic data from the upper surficial sediment (~50 cm, considering the pulse length of 0.54 m) were used to calculate values of acoustic impedance.

The ASCS is a normal incidence, narrow beam-width, multi-frequency, high-resolution, and digital acoustic profiling system that records and displays, in the form of a seismic waterfall plot, real-time echo return intensity (amplitude) from seafloor and subbottom sediments (Fig. 2). This system is typically operated using a short pulse length (0.1 to 0.3 milliseconds) with a narrow-beam transducer (12° at 11 kHz). The narrow beam method is intended to concentrate the acoustic energy within a small area of the seafloor to reduce extraneous acoustic scatter and anomalous late returns that occur from outer limit of the non-planar wave of wide-beam system (Walter, 1998). Using acoustic technique, sediment properties can be mapped at real time during the survey, and can be reprocessed using SSC in laboratory (Fig. 2).

The ASCS and SSC based on multi-layer acoustic theory (Clay and Medwin, 1977) use echo-strengths reflected from sediment to compute acoustic impedance (Lambert, 1988; Walter et al., 1998). The reflected pulses are digitized and stored on an optical disk at a sampling rate of 125 kHz for processing (Fig. 2). This reflection coefficient (R) is defined as the portion of the sound pressure wave reflected off the seafloor, divided by the incident sound pressure wave impinging on the bottom; that is, the ratio of the reflected wave (Pr) to the incident wave (Pi). Therefore;

$$R = Pr/Pi$$

and, for a normally incident acoustic wave, this reflection coefficient is related to acoustic impedance by the following relationship;

$$R = Pr/Pi = \{(\rho_2 V_2) - (\rho_1 V_1)\}/\{(\rho_2 V_2) + (\rho_1 V_1)\} = (Z_2 - Z_1)/(Z_2 + Z_1)$$

where ρ_1, V_1, Z_1 and ρ_2, V_2, Z_2 are the density, compressional wave velocity and acoustic impedance values in the water column and the surficial sediments, respectively. This system uses an assumed seawater impedance of 1.5×10^5 g/cm^2 s. From the above equation, the sediment impedance Z_2 is determined (Walter, 1998). Therefore, the grain size data including geotechnical properties can be estimated from empirical relationships between acoustic impedance and geotechnical properties (Richardson and Briggs, 1993).

3.3. Calibration and Re-Processing Using SSC System

The calibration factor for echo strength amplitude of SSC was determined by matching values of impedance acquired from five core samples (Table 1) collected on the acoustic track line. Impedance values were averaged from the upper 50 cm of core data and from 5 acoustic ping data along seismic tracks which were closest to the core samples. Acoustic impedance obtained from ground truth core and SSC were

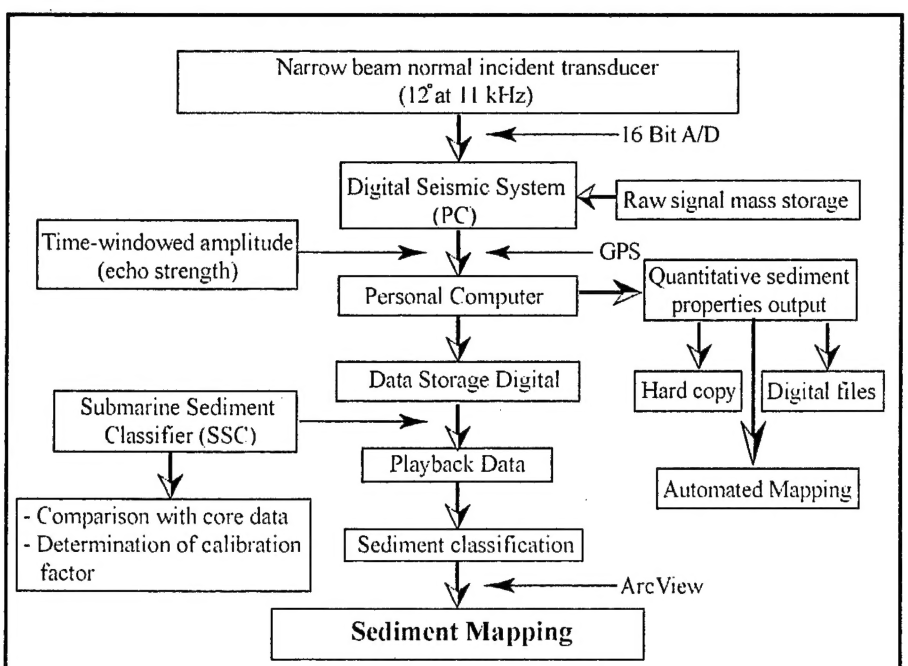

Fig. 2. Block diagram of Acoustic Sediment Classifier System (ASCS). Acoustic data can be playback and reprocessed using Submarine Sediment Classifier (SSC) at laboratory.

Table 1. Sediment properties measured and estimated from the five cores and ASCS in order to determine calibration factor.

Locations	Methods	Impedance (10^6 kg/m^2 s)	Density (g/cm^3)	Attenuation (dB/m kHz)	Porosity (%)	Grain size (ϕ)	Velocity (m/s)	Sediment type
599C-1	Core	2.89	1.84		49.9	7.9	1571	Sandy clay
	ASCS	2.94	1.84	0.61	51.9	4.75	1619	Mud
599C-6	Core	2.18	1.45		73.7	6.23	1500	Clayey sand
	ASCS	2.09	1.39	0.10	80.9	8.92	1537	Mud
599C-8	Core	3.33	1.99		40.9		1676	
	ASCS	3.40	2.00	0.51	40.7	2.49	1705	Sand
599C-9	Core	3.28	1.96		42.5	2.5	1675	Clayey sand
	ASCS	3.20	1.94	0.70	46.0	3.62	1669	Sand
299C-10	Core	3.48	2.04		37.9		1712	
	ASCS	3.43	2.01	0.51	41.1	2.5	1721	Sand

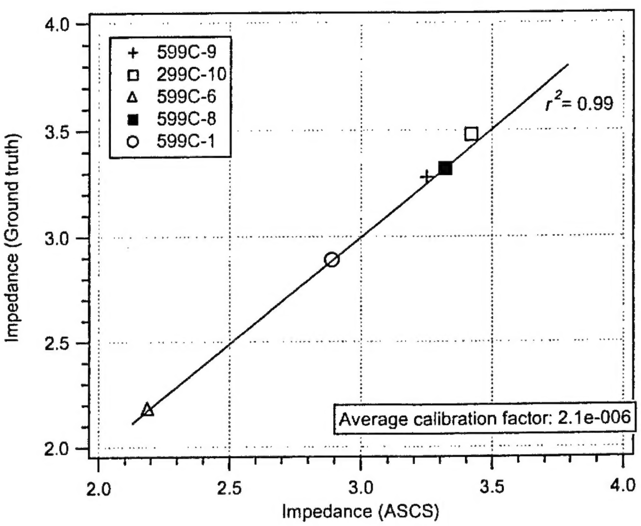

Fig. 3. Correlation of impedance values obtained from the core (ground truth) and acoustic (ASCS) data used for determination of calibration factor. The calibration factor is averaged by the values obtained from five cores. Note that two data show good correlation (r^2=0.99).

highly correlated (r^2=0.99) (Fig. 3). Therefore, the calibration factor of 2.1e-006 can be used with confidence to predict value of sediment properties at other sites along the 200 km of track lines. This echo strength calibration was used for re-processing the entire data set. After re-processing using SSC, the colored track plots (acoustic impedance and grain size) are created by ArcView software (Fig. 2).

4. RESULTS AND DISCUSSION

4.1. Comparison of Ground Truth and ASCS Data

Table 1 contains values of the sediment properties (acoustic impedance, bulk density, attenuation, porosity, sound speed, and mean grain size) obtained from five core samples (average values for the upper 50 cm) and the associated acoustically predicted ranges (ASCS data) in proximity to these sites. The acoustic data in Table 1 represents an average value for five consecutive pings at the closest point along any track line to the core sites. In most cases, the ASCS acoustic footprint (a half size of an acoustic footprint=tan 6° (water depth), for example, 5.26 m in water depth of 50 m) did not include the exact location of the core, which may partly account for the difference between values of ground truth measurements and acoustic predictions. In addition, the differences may be caused by sediment disturbance including compaction or loss during core collection, and compaction or grain reorientation during transport and measurement, frequency dispersion, sound speed anisotropy, or by the natural fine scale variability of sediments (Richardson, 1986; Richardson et al., 1997). Frequency dispersion may result in values of sound speed measured at 500 kHz (ground truth data) as much as 50 m s^{-1} higher than ASCS acoustic data, acquired as frequency of 11 kHz, especially in sandy sediments (Williams et al., 2002). Richardson (1986) shows considerable vertical and horizontal variability of sound speed and other sediment physical properties at centimeter to meter scales. The longer wavelength and larger footprint tend to average out this fine-scale variability. In spite of the differences between ground truth measurements and acoustic predictions, the relationship between ground truth (core samples) and acoustic data are nearly identical (Fig. 4). Therefore, acoustic techniques can be used with confidence to determine sediment properties of seafloor.

However, the ability of an acoustic sediment classification system to accurately predict values of sediment physical properties and to map sediment provinces is dependent on accurate estimation of sediment impedance from the acoustic returns and applicability and uncertainty associated with the empirical regressions used to predict sediment properties from sediment impedance. As described in the previous figures (Figs. 3 and 4), acoustic returns provide a reasonable estimate of acoustic impedance compared well to ground truth data. The large confidence limits of the prediction probably result more from issues associated with

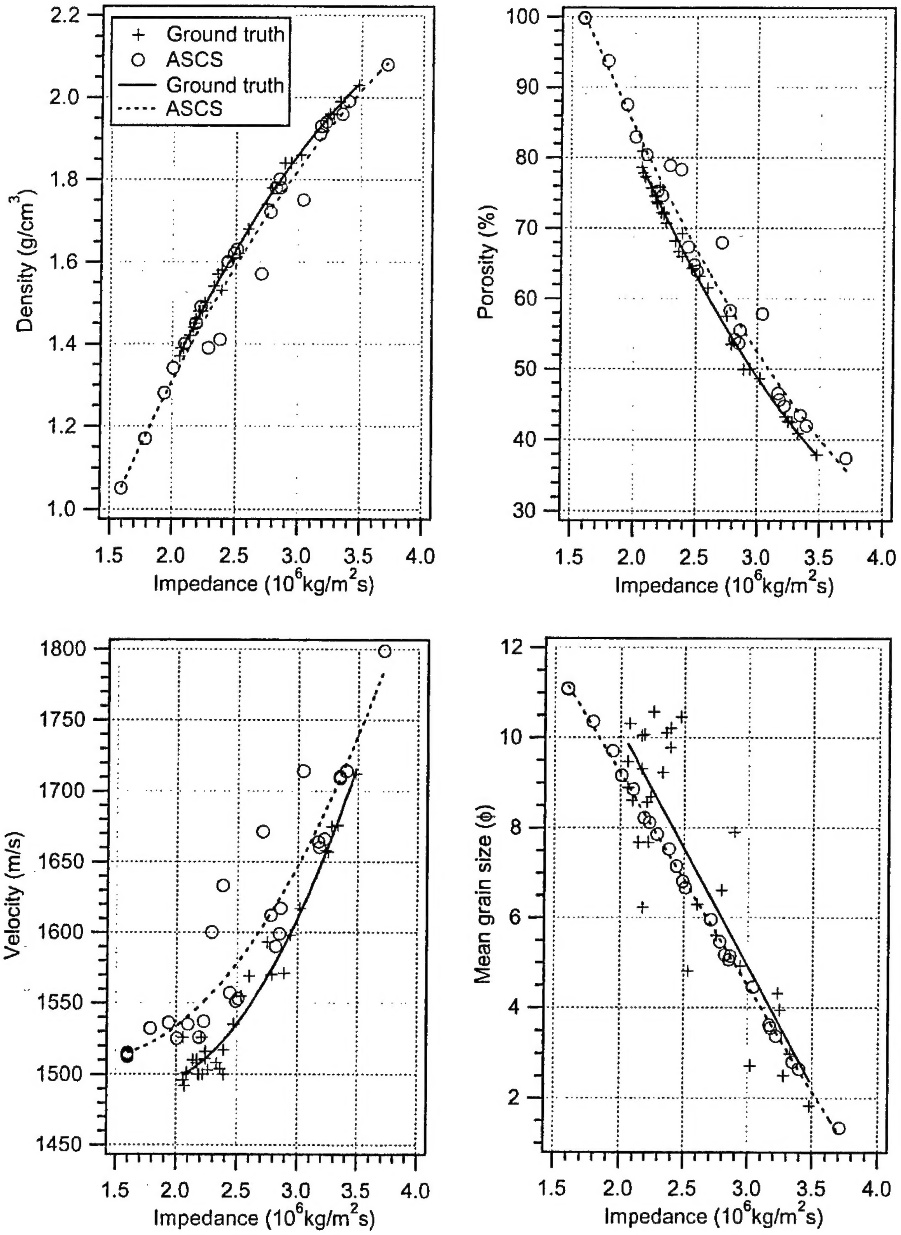

Fig. 4. Relationships between impedance and physical properties obtained from ground truth (20 cores) and ASCS data around the core sites. The ASCS is done under the same identical setting for entire data sets. The scattering of the data is due to the locations of core sites and acoustic track lines are not exactly the same. But the trends are nearly identical.

collocation of laboratory and acoustic estimates of impedance in these the highly variable sediments than from sediment disturbance, frequency dispersion or any inherit uncertainty associated with the calibration factor.

4.2. Areal Distribution of Sediment Types

Acoustic images and colored track plots using data sets processed by ASCS provide highly detailed maps of the distribution of values of sediment properties (acoustic impedance, grain size) in the northeastern Gulf of Mexico.

Acoustic impedance, the product of compressional wave velocity and bulk density, is computed using acoustic echo-strength reflected at the seafloor. Values of impedance range from 1.60 to 4.00×10^6 kg/m^2 s, with both the highest and lowest values of impedance found in the deepest water depth of the study area (Fig. 5).

Based on acoustic impedance values (Lambert, 1988), the study area may be geographically divided into four sediment types (Fig. 5; Table 2): i.e., type A (impedance, range =1.6–2.0×10^6 kg/m^2 s), type B (impedance, range=2.01–2.40 ×10^6 kg/m^2 s), type C (impedance, range=2.41–2.90×10^6 kg/m^2 s), type D (impedance, range=2.91–4.0×10^6 kg/m^2 s). The boundaries in each type are distinct based on sediment impedance, and the track plot of mean grain size (Fig. 6) also matches well with the acoustic impedance map (Fig. 5).

Sediments in type A have the lowest values of impedance (with a range of 1.6–2.0×10^6 kg/m^2 s) and are mainly present at the southernmost and southwestern part of the study area but also occurs intermittently at the eastern tip (Figs. 5 and

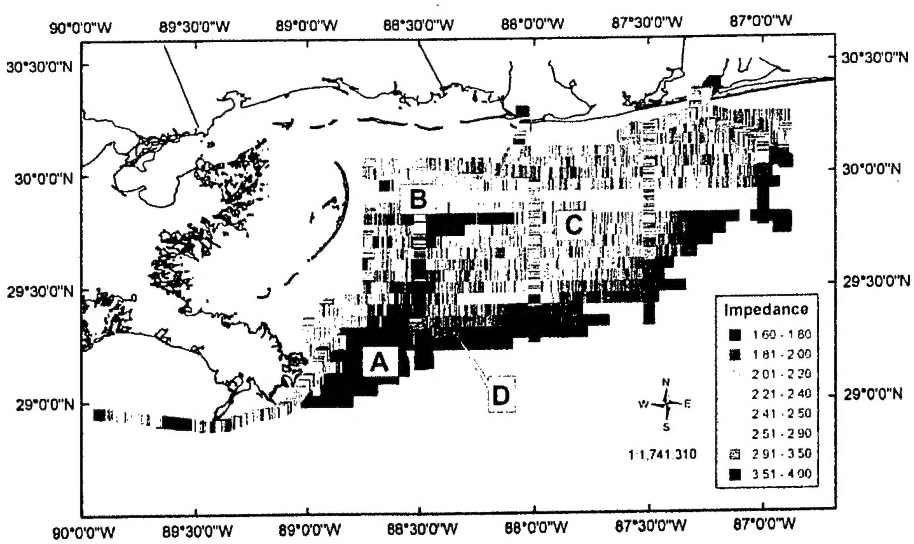

Fig. 5. Colored track plot of surficial sediment acoustic impedance (10^6 kg/m^2 s) processed by ASCS. The plotting of impedance data is limited from 1.6 to 4.0×10^6 kg/m^2 s, considering ground truth data and the quality of acoustic signals. The sediment patterns based on acoustic impedance are grouped into provinces A, B, C, and D.

Table 2. Impedance and grain size values of types A, B, C, and D divided by acoustic data.

Types	Impedance (10^6 kg/m^2 s)	Grain size (ϕ)	Sediment type
Type A	1.60-2.00	9.1-10.0	sandy and/or silty clay
Type B	2.01-2.40	6.1-9.0	sand-silt-clay and/or clayey sand
Type C	2.41-2.90	3.1-6.0	silt and fine sand
Type D	2.91-4.0	0.2-3.0	medium/coarse sand

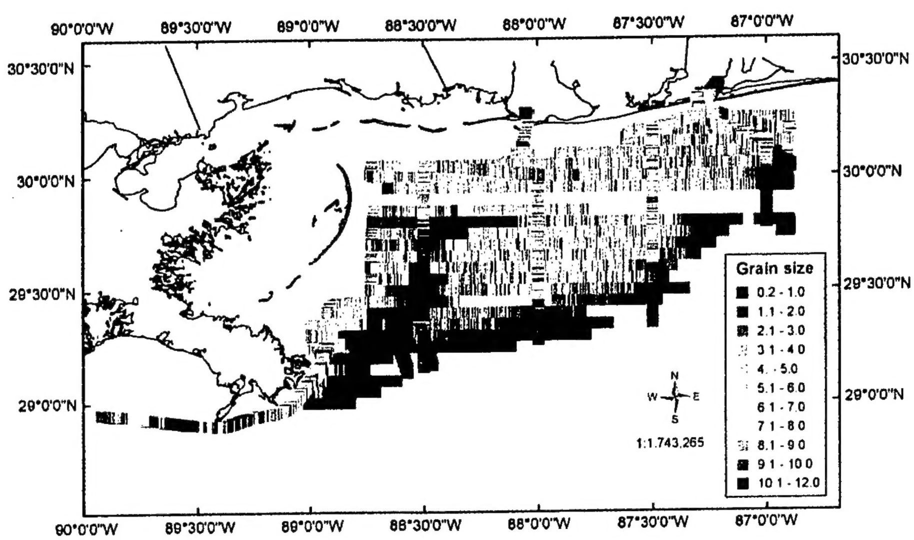

Fig. 6. Colored track plots of surficial sediment grain size (ϕ) processed by ASCS. The distribution pattern is similar to Figure 5. These distributions are similar to the previous results (Ludwick, 1964; Mazzullo and Bates, 1985; Sawyer et al., 2001) collected by core and grab samples.

6). By acoustic data, the sediments of type A are sandy clay and/or silty clay having a 9.1–10ϕ in mean grain size (Table 2).

Type B exists at the westernmost part of the study area including Mississippi Delta (Figs. 5 and 6). Acoustic impedance and mean grain size of type B calculated from acoustic data is 2.01 to 2.40×10^6 kg/m^2 s and 6.1–9.0ϕ. Thus, type B is sand-silt-clay and/or clayey sand (Table 2). Types A and B are most likely deposited by the west-flowing longshore current along the barrier islands well developed in the northern part of the study area (Boone, 1973). These islands have been migrating to the west at rapid rates (Waller and Malbrough, 1976; Bymes et al., 1991). Wave energy in the Northern Gulf of Mexico generally increases to the east due to the sheltering effect of the Mississippi Delta (Richard, 1997). Thus, longshore transport of sediment along this northern coast is generally thought to be east to west, Types A and B correspond closely to Holocene sand, silt, and clay deposited in association with the Mississippi Delta (Ludwick, 1964; Mazzullo and Bates, 1985).

Sediments from type C (impedance, 2.41–2.90×10^6 kg/m^2

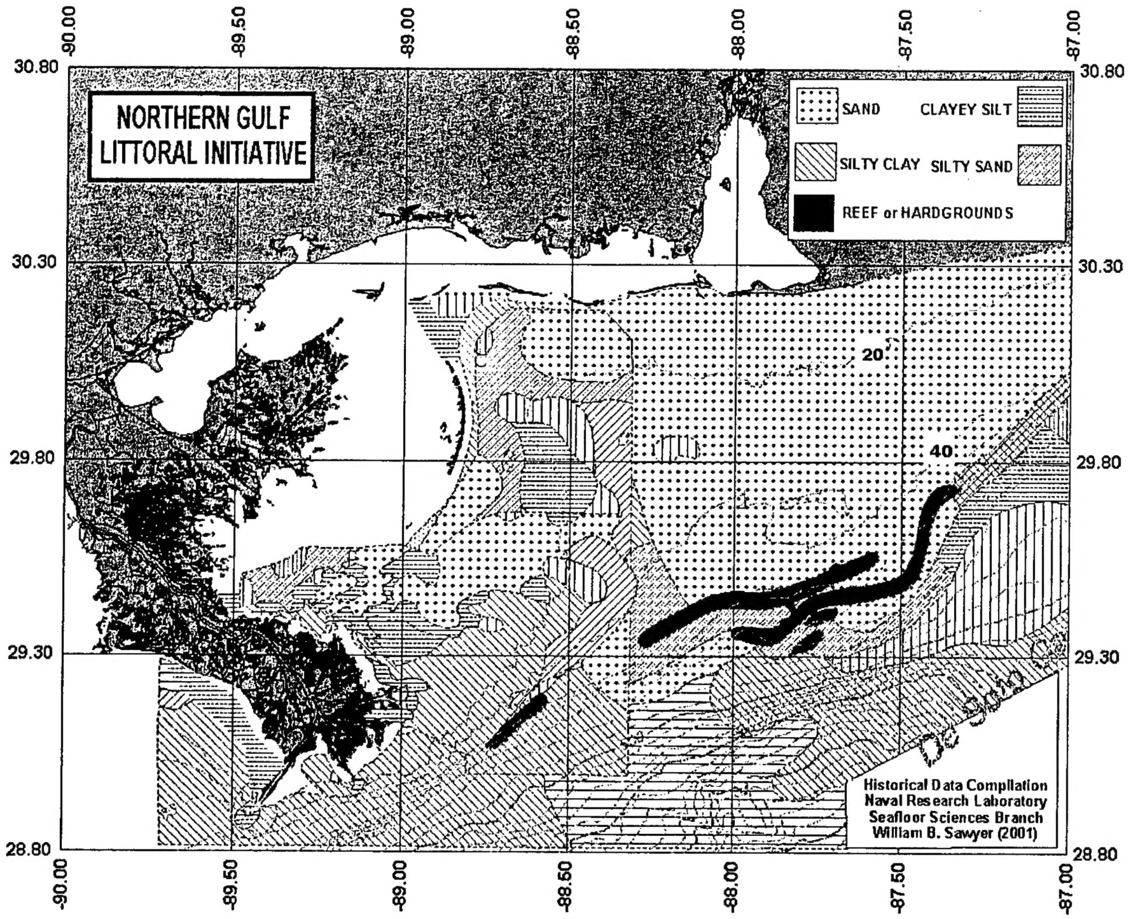

Fig. 7. Map of bottom sediment distribution modified by Sawyer et al. (2001) based on historical data from core and grab samples. The distribution pattern matches with the present result grouped by types A, B, C, and D. Contours in meters.

s) are widely distributed in the central and northern part of the study area (Figs. 5 and 6). The sediments determined by acoustic data are silt and fine sand with a mean grain size of 3.1 and 6.0 ϕ (Table 2). Type C is probably regarded as a relict Pleistocene deposit (Mazzullo and Bates, 1985; Kindinger, 1989).

Sediments in type D (impedance, 2.91–4.0 10^6 kg/m^2 s) are distributed in a narrow east-northeast to west-southwest band (red segment of the track lines) approximately at the 75 m shelf break (Figs. 5 and 6). By acoustic data, the sediments are medium to coarse sand with the range of 0.2 to 3.0 ϕ in mean grain size (Table 2). This indicates the presence of hard bottom as well as coarse sand and/or gravel. Type D is compared well with Mississippi-Alabama Reef and Interreef types described by Mazzullo and Bates (1985).

Based on the historical (Mazzullo and Bates, 1985; Kindinger, 1989) and NGLI data (Sawyer et al., 2001) illustrated by cores and grabs data, the surficial sandy sediments corresponding to type C are widely distributed in the northeastern part (Fig. 7), and the clayey sediments compared to types A and B coincide with the distribution patterns predicted by ASCS. Also the location of reef and hard ground relatively matches with that of type D (Fig. 7). The sediment distributions of the study area characterized by shallow water depth (Sawyer et al., 2001) were most likely reworked and redistributed by waves, tides, currents, and sea level change (Coleman, 1988).

In summary, the sediments covering the study area are probably the current Holocene sediments (largely type A and some parts of type B), mixed sediments (some parts of types B and C) re-settled by reworking of Pleistocene and Holocene deposits, and relict sediments (some parts of type C and largely type D) deposited during Pleistocene.

5. CONCLUSIONS

The relationship of impedance value measured and predicted from core data and acoustic data shows close agreement. The slight difference between core data and acoustic data is due to the discrepancy (navigation errors) of acoustic track line and core location selected for comparison. In addition, the difference may be caused by sediment disturbance during core collection, by frequency dispersion, and by natural variability.

By sediment classification using ASCS, the study area may be divided into four separate provinces (types): i.e., sandy and/or silty clay (type A, impedance, 1.6–2.0×10^6 kg/m^2 s), sand-silt-clay and/or clayey sand (type B, impedance, 2.01–2.40×10^6 kg/m^2 s), silt and fine sand (type C, impedance, 2.41–2.90×10^6 kg/m^2 s), and medium/coarse sand (type D, impedance, 2.91–4.0×10^6 kg/m^2 s).

As a result, this sediment classification coincides well with the previous results reported by ground truth. Therefore, the ASCS can effectively be used to define and classify sediments and sediment provinces.

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